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A FEASIBILITY STUDY OF METHODS FOR STOPPING THE DEPLETION OF OZONE OVER ANTARCTICA

Final Report

Submitted to:

Dr. Wallace T. Fowler

May 6, 1988

Presented by:

Project Equilibrium

Department of Aerospace Engineering
and Engineering Mechanics
The University of Texas at Austin

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EXECUTIVE OVERVIEW

The purpose of the study conducted by Project Equilibrium was to determine ways of stopping the ozone depletion in the ozone hole over Antarctica. The three basic objectives of the study were as follows:

1. To define and understand the phenomenon of the ozone hole
2. Determine possible methods of stopping the ozone depletion
3. Identify unknowns about the hole and possible solutions.

Two basic ways of attacking the problem were identified. First is replenishment of ozone as it is being depleted. Second is elimination of ozone destroying agents from the atmosphere. The second method is a more permanent form of the solution.

Any design of a possible solution requires specification of replenishment or elimination mechanisms, delivery systems, power systems, and support systems. Possible replenishment mechanisms are photocatalysis and electric discharge. Elimination mechanisms include molecular sieves and precipitates. The delivery systems may be either ground-based, lighter-than-air, or heavier-than-air. Possible power supplies are nuclear, chemical, wind, solar, and microwave. Support systems include any required ground stations, vehicle navigation system, and weather and ozone monitoring facilities.

By no means are the possibilities presented in this report complete. Since a detailed analysis was beyond the scope of this study, the final product is a set of recommendations in the form of questions that will need to be answered by future studies on the problem.

The hole may not be critical at the present, and the ozone loss may be a phenomenon peculiar to the South Pole, but in-depth studies into possible solutions should be made now before the problem ever does become critical.

ACKNOWLEDGEMENTS

We would like to thank Tom Gray of the University of Texas, Department of Aerospace Engineering and Engineering Mechanics for the helpful discussions on Antarctic meteorology and for his references. We also appreciate the help of Brendon O'Conner, the project manager of the design group, SECO (Selene Engineering Co.) in locating some references on atmospheric chemistry over Antarctica. Finally, we would like to thank George Davis, the teaching assistant of the spacecraft/mission design class, and Dr. Wallace T. Fowler for his suggestions, advise, patience, and good humor.

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1. INTRODUCTION

The springtime amounts of stratospheric ozone over Antarctica have decreased by up to 50 percent since 1977. Global amounts of stratospheric ozone are harder to assess, but a decreasing trend has been observed. According to one theory, the cause of the ozone depletion is chlorofluorocarbons (CFC's) which release ozone-destroying chlorine atoms in the stratosphere. CFC's are very stable compounds in the lower atmosphere and have a lifetime of about 75 to 100 years. Therefore, even if all use of CFC's were to stop today, the depletion of ozone will continue. If ozone depletion becomes a greater problem, methods of solution other than a mere ban on the CFC usage must be implemented.

This report by Project Equilibrium discusses some possible methods of solution for stopping the depletion of ozone over the South Pole based on the CFC theory. Although the focus of this study was on the Antarctic ozone hole, the results may be applicable to the global ozone situation. This study is by no means complete; there may be other more viable methods. It is the hope of the Project Equilibrium team that the work presented here will inspire more thorough studies into solving the problem of ozone depletion.

The goals of Project Equilibrium were as follows:

1. To define and understand the problem of ozone depletion over the South Pole.

2. To determine possible methods and configurations for stopping the depletion of ozone.

3. To identify unknowns about the problem and design of possible solutions.

Since a detailed analysis of possible solutions was beyond the scope of this study, the final product is a set of recommendations for future design studies. Topics that were not addressed by Project Equilibrium or were beyond the scope of this project are as follows:

1. Step-by-step instructions for suggested experiments
2. Exact quantities or qualities
3. Cost Analysis
4. Political issues involved with this global problem.

The main body of the report is divided according to the goals of the study. First, the problem of ozone depletion and the ozone hole, as it is understood by this group, is explained in Section 2 - Understanding the Problem. Possible configurations of stopping the depletion are described in Section 3 - Possible Solution Methods. In this section, individual systems required for a complete design are identified and then possibilities for each system are briefly described. In Section 4 - Future Work, experiments are suggested to answer some of the unknowns or questions about the problem and possible solution methods. A final assessment of the study is given in Section 5 - Conclusions. Finally, management status and cost status are summarized in Section 6. A copy of the proposal is included in the Appendix.

2. UNDERSTANDING THE PROBLEM

This section describes the nature of ozone and the ozone hole over Antarctica. The two most prominent theories for the hole are presented and the pertinent meteorological conditions over Antarctica are described.

2.1 WHAT IS OZONE?

Ozone (O_3) is a three atom modification of molecular oxygen (O_2) and plays a critical role in the radiation balance of the earth. It shields the biosphere from lethal ultraviolet radiation from the sun. Existence of ozone as a constituent in the natural troposphere was chemically proven by Houzeau (1858). Hartley (1881) was the first to point out that ozone is a normal constituent of the higher atmosphere. Lord Rayleigh gave the first satisfactory determination of the absorbing medium. Chapman (1930) proposed a series of processes that lead to ozone formation, known later as the Chapman mechanism :

$$O_2 + h\nu \Rightarrow O + O \quad (1)$$
$$O + O_2 + M \Rightarrow O_3 + M \quad (2)$$
$$O_3 + h\nu \Rightarrow O + O_2 \quad (3)$$
$$O + O_3 \Rightarrow O_2 + O_2 \quad (4)$$

where $h\nu$ is ultraviolet radiation and M is a third body required to carry off the excess energy of the association process. Reaction (4) is the only ozone loss process resulting in a net ozone loss. Recent measurements have led scientists to believe that reaction (4) is not sufficient to account for the observed ozone destruction rate. Thus, it was suggested that catalytic processes can accelerate reaction (4):

$$X + O_3 \Rightarrow XO + O_2 \quad (5)$$
$$XO + O \Rightarrow X + O_2 \quad (6)$$
$$O + O_3 \Rightarrow 2O_2 \quad (7)$$
$$(X = OH,\ NO,\ CL)$$

In natural atmospheric conditions, ozone settles into a dynamic equilibrium in which the rate of its formation is equal to the rate of its destruction by ultraviolet radiation. It can be transported vertically and horizontally by atmospheric motions or by diffusional processes driven by density variations [Whitten, 1985].

2.2 THE OZONE HOLE

In May 1985, the British Antarctic Survey team announced that the springtime amounts of ozone in the atmosphere over Halley Bay, Antarctica, had decreased by more than 40 percent between 1977 and 1984. The report was soon confirmed by other groups which showed that the region of ozone depletion was wider than the continent and that it extended roughly from 12 to 24 kilometers in altitude. Essentially, there was an ozone-poor hole in the polar atmosphere.

In 1987, two NASA planes based at Punta Arenas, Chile and carrying a total of 21 experiments conducted 25 flights over Antarctica and through the hole between August 17 and the end of September. This was the Antarctic Airborne Ozone Experiment which left scientists with an enormous amount of data on both meteorological and chemical conditions over Antarctica. Preliminary analysis revealed a complex picture of the hole..Scientists are hoping to have papers published in the peer reviewed literature by next year.

The hole develops each southern spring within a vortex, peculiar to the south pole. This vortex isolates an air mass over Antarctica during a large part of the year. The amount of ozone in this air mass begins decreasing in late August and early September , stabilizes in October, and then increases again in November when the vortex dissipates [Stolarski, 1988].

2.3 THEORIES

Two essential theories were suggested by scientists after the disclosure of the hole. One theory assumes pollutants are the cause for ozone depletion. Starting from 1971 when supersonic airplanes where expected to roam the skies, investigators worried that the exhausted water vapor and nitrogen oxides would catalytically destroy ozone. Rowland and Molina (1974) pointed to a similar destructive role played by the chlorine atoms which are released from man-made chlorofluoromethanes or chlorofluorocarbons (CFC's). CFC's consist of chlorine, fluorine, and carbon. They are used as working fluids in refrigerators and as propellents in aerosols. In the lower atmosphere, the released molecules are stable and harmless. When they reach the stratosphere through atmospheric transport mechanisms, chlorine atoms are liberated by ultraviolet radiation from CFC. These chlorine atoms are then involved in a catalytic process through which they destroy up to 100,000 ozone molecules before precipitating to the lower atmosphere. [Rowland, 1987] One possible destruction mechanism is summarized in the following equations:

$$CCl_2F_2 + h\nu \Rightarrow Cl + CClF_2 \quad (8)$$
$$Cl + O_3 \Rightarrow ClO + O_2 \quad (9)$$
$$ClO + O \Rightarrow Cl + O_2 \quad (10)$$

This mechanism is effective at an altitude of about 40 km, at mid- and equatorial latitudes. It probably does not contribute much to the ozone depletion in the Antarctic which is mainly occuring at lower altitudes. The amount of sunshine in early spring, when the ozone hole appears, is not sufficient to generate the monatomic oxygen in amounts required for reaction (10). [Zurer, *Antarctic* ..., 1987] So chemists have suggested other mechanisms which would not involve an oxygen atom. The one that is considered most likely involves the dimer of chlorine monoxide:

$$Cl + O_3 \Rightarrow ClO + O_2$$
$$Cl + O_3 \Rightarrow ClO + O_2$$
$$ClO + ClO + M \Rightarrow (ClO)_2 + M$$
$$(ClO)_2 + h\nu \Rightarrow Cl + ClOO$$
$$ClOO + M \Rightarrow Cl + O_2 + M$$

These catalytic processes do not operate unfettered. One important reaction leads to the combination of a chlorine monoxide with another molecule to form a stable product that temporarily acts as a chlorine reservoir:

$$ClO + NO_2 \Rightarrow ClONO_2$$

Unfortunately, these reservoirs eventually absorb a photon, or react with other chemicals, to break apart and free the chlorine atom which then resumes the catalytic cycle. That these retarding mechanisms are relatively ineffective over the Antarctic may be explained by the role that the stratospheric polar clouds play in fixing or freezing the potential reservoir molecules such as nitrogen oxides from combining with chlorine monoxide to form the reservoir molecule chlorine nitrate. These clouds might also facilitate the conversion of chlorine reservoirs into active chlorine through mechanisms like those shown below:

$$H_2O + ClONO_2 \Rightarrow HNO_3 + HOCl$$

or

$$HCl + ClONO_2 \Rightarrow HNO_3 + Cl_2.$$

Scientists also focused on meteorological causes which would simply redistribute ozone without destroying it. They claim that peculiarities of Antarctic meteorology, such as the polar vortex, impede the ozone-rich air of the equator from reaching farther south until late in the Antarctic spring when the vortex breaks up with the warming of the atmosphere. Support for this theory could come from analysis of temperature distribution in the Antarctic region. If springtime circulation is not able to reach the polar region, one would expect a decrease both in temperature and ozone. Although no significant temperature changes were observed during the period of hole formation, reports by the 1987 Airborne Antarctic Ozone Experiment pointed to a dramatic decrease in ozone levels over a large area in one day. Such a dramatic change can best be explained with the air movement theory [Stolarski 1988].

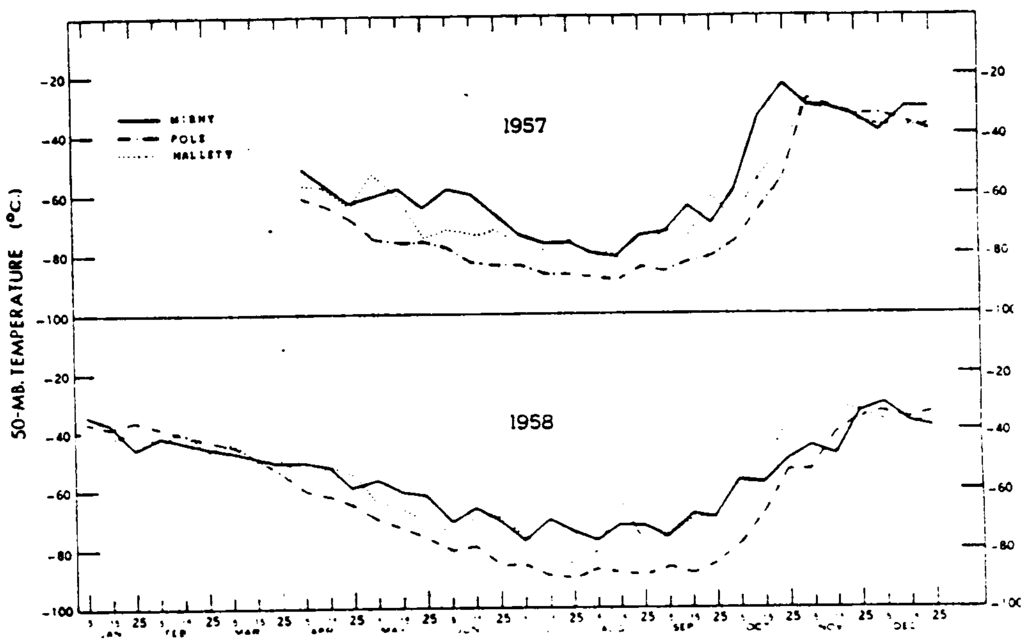
Another dynamical theory suggests that the ozone-poor air from the troposphere or the lower stratosphere rises and displaces the air parcels that would normally be ozone-rich. [Zurer, *Complex...*, 1987] At the present, both chemical and dynamical theories are used to explain the hole.

2.4 ANTARCTIC METEOROLOGY

In addition to the nature of the ozone hole, the weather conditions over Antarctica must be understood, since the weather is critical in planning any operation over Antarctica. Pertinent meteorological factors include temperature, wind, and sunshine hours.

Shown in Figure 2.1 are the temperature distributions over Antarctica in 1957 and 1958 for a pressure altitude of 50 millibar measured from three stations. The 50 millibar pressure altitude approximately corresponds to the altitude of the ozone layer. From the figure, it can be seen that the temperature decreases gradually in January or the beginning of the Antarctic fall season. A minimum temperature of about -80 °C is reached in late July to early August. Then starting in late August, there is a sharp rise in temperature to a summer-time peak of about -30 °C. [Ropar, 1960]

Associated with the cooling period is the formation of a cold cyclonic circulation beginning in March. As the cooling continues, the vortex becomes tighter with greater temperature and pressure gradients. With the return of the sun in the spring months of



50-mb. temperatures (° C.) at 10-day intervals, 1957 and 1958, at Mirny (solid line), South Pole (dashed-dotted line), and Hallett (dotted line).

Figure 2.1 Temperature Distribution

September and October, however, the low pressure center of the vortex begins to fill. Then around November, there is a transitional period in which the stable winter-time cyclonic circulation transforms into a stable summer-time anticyclonic circulation. During the rapid spring-time warming of this transitional period, the cyclonic circulation becomes unstable and wind speeds and shears may reach a maximum of over 150 knots. The stable summer-time anticyclonic circulation, on the other hand, is generally composed of weak winds and a uniform temperature field. [Moreland, 1959]

Wind conditions over the surface of Antarctica is less severe. The wind speeds range up to about 50 knots depending on the location and the time of the year and day. [Vowinckel, 1957]

Precipitation over Antarctica consists almost exclusively of snow. Heavy winds which usually accompany snow, however, make it difficult to distinguish between falling and drifting snow. Because of the strong cyclonic activity, there is frequent precipitation, but the low temperatures permit very little water vapor content in the atmosphere and the intensity of precipitation is usually low. [Loewe, 1957]

Due to the lack of heavy and protective water-vapor-rich atmospheric layer which would absorb and reradiate long-wave radiation to earth, the Antarctic surface readily loses heat energy into space. Hence, outgoing terrestrial radiation greatly exceeds incoming solar radiation resulting in strong surface cooling. This gives rise to the characteristic temperature inversion in which the temperature increases from the surface to about 1,000 ft in altitude.

As a representative sample of sunshine hours over Antarctica, the data for Cape Evans station is listed in Table 2.1. Cape Evans station is located in the South Pacific Coast of Antarctica in McMurdo Sound at 77.5 $^{\circ}$S latitude. The table shows the monthly percentage of the possible number of sunshine hours at the surface for the months of July to December. [Vowinckel, 1957]

Table 2.1 Sunshine Hours over Cape Evans

Month	Monthly % of possible sunshine hours
July	0
August	0
September	>24
October	>38
November	48
December	48

Daylight may or may not be an important factor depending on what operations will be used; for instance, flying vehicles with solar arrays will be restricted to flight during daylight hours.

2.5 ATMOSPHERIC MODEL

The Antarctic atmospheric model that was used for the determination of possible replenishment or elimination mechanisms or systems, delivery and power systems, and the ground support facilities is summarized in Table 2.2.

Table 2.2 Atmospheric Model

Average Altitude of Ozone Layer	20 km	
Pressure	5 - 10 kPa	
Temperature[1]	221.7 °K (-51.5 °C)	
Density[1]	39×10^{-3} kg/m^3	
Volume of Hole (approx.)	155×10^6 km^3	
Normal Ozone Concentration[2]	320 ppb	4.1×10^{34} molecules
Present Ozone Concentration[3]	200 ppb	2.6×10^{34} molecules
Current CFC Concentration[4]	300 ppt	3.8×10^{31} molecules

1. U.S. Standard Atmosphere, 1962 (Geopotential Altitude)
2. 1957 - 1973 value from Rowland, 1987
3. 1984 value from Rowland, 1987
4. 1986 value from *Current Issues in Atmospheric Change*, 1987

3. POSSIBLE METHODS OF SOLUTION

The design of possible solutions requires specifying the mechanism for stopping the ozone depletion, the delivery systems used for delivering the mechanisms, the power systems needed for the mechanisms and the delivery systems, and any support systems. Possibilities for each system are described in this section.

3.1 MECHANISM FOR STOPPING OZONE DEPLETION

There are basically two types of mechanisms for stopping the ozone depletion. The first is replenishment of ozone as it is being depleted. Second is elimination of ozone-destructing agents from the atmosphere. Although the second type is more practical since it eliminates the cause of the problem, both types are described below.

3.1.1 Replenishment Mechanism

3.1.1.1 Photocatalysis

Photocatalysis involves introducing catalysts that would accelerate the natural production of ozone. Molecular oxygen is excited, favoring ozone formation:

$$(3/2)\,O_2 \Rightarrow O_3,$$

after exposure to ultraviolet radiation. Mercury vapor is a catalyst used in industry. A harmless photocatalyst that would play the role of mercury in the atmosphere is yet to be determined.

3.1.1.2 Electric Discharge

Silent electrical discharge is a common method of producing ozone in industry. [Ardon, 1965] A device called an ozonizer is used to create the electric discharge between electrodes connected to a high voltage source of about 5,000 to 30,000 volts. A di-electric layer and an air gap separate the electrodes. A flow of oxygen or air which passes through becomes enriched with ozone after the following reaction:

$$e^- + O_2 \Rightarrow 2O + e^-$$
$$O + O_2 + M \Rightarrow O_3 + M$$

A sample ozonizer with cooling water as the second electrode is shown in Figure 3.1.

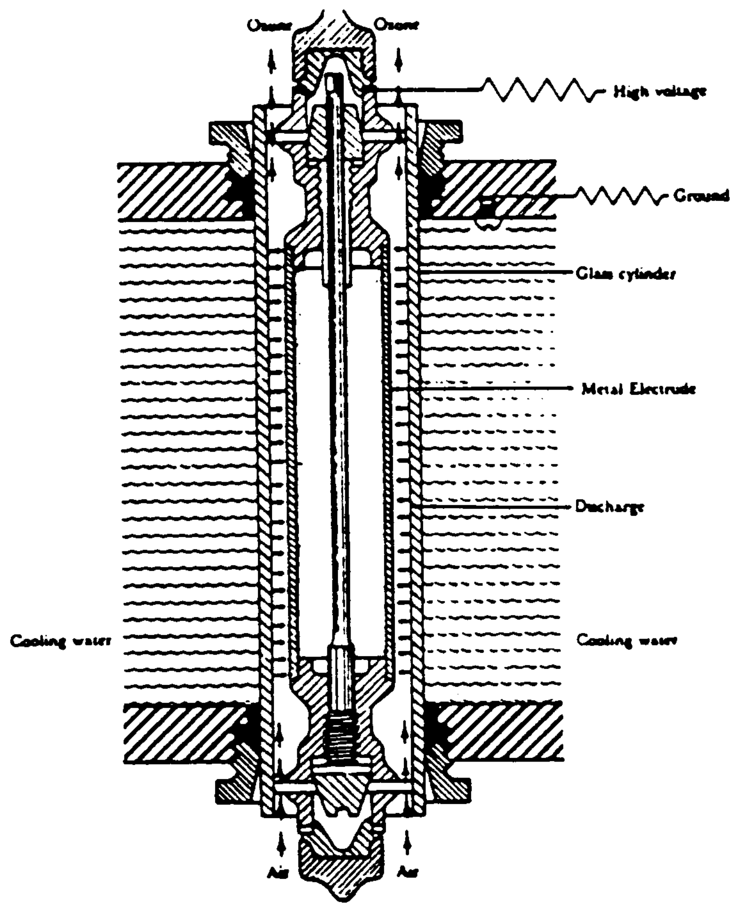


Figure 3.1 Ozonizer

Silent discharge is more efficient than spark-ozone discharge because more efficient cooling of the gas is possible using the silent method. This minimizes ozone loss due to thermal decomposition or decomposition by collision with an inert molecule. A pressure of 102 kPa is optimal. In industry, rates of ozone production of a 150 g/kWh can be achieved using pure oxygen, and the emerging mixture from the ozonizer contains about 2 % to 5 % ozone. In industry, ozone is usually separated from oxygen by absorption on silica gel then desorbed by nitrogen or argon. Oxygen may be recycled in the ozonizer. The electric discharge process is not favored by the presence of nitrogen, moisture or freon which lead to radicals that destroy ozone. The systems required to carry out the generation mechanism are:

- Supply system
- Purification system
- Instrumentation, control and energy supply
- Ozone generators.

3.1.2 Elimination Mechanism

3.1.2.1 Molecular Sieves

Molecular sieves have the ability to adsorb fluids - both gases and liquids. The amount of gas or liquid adsorbed when equilibrium is established, is a function of both the adsorbent and adsorbate. The lower the temperature and the higher the pressure, the more material that will be adsorbed. The adsorbent to be used must have the following qualifications:

- high capacity for adsorbates
- high selectivity
- ability to be regenerated and reused
- chemically inert
- inexpensive.

Adsorbents in use today fall into four major categories:

1. aluminum oxide
2. activated carbon
3. silica gel
4. crystalline zeolites.

Zeolites are most promising for the application at hand. They are a family of hydrated silicates which have similar compositions and properties. The subgroup that contains the molecular sieves is characterized by a cubic or rhombohedral structure and consist of three dimensional 4-fold or 6-fold rings of tetrahedra. They are selective for polar molecules. The Linde Company, a Division of Union Carbide Corporation, produced three types of zeolites: 4A, 5A, 13X, each having an affinity for a class of molecules. The molecular sieve 5A adsorbed Freon-12. Chlorinated compounds such as HCl, Cl_2, CH_3Cl, CH_2Cl_2 are adsorbed by synthetic zeolites. Side effects of marketed molecular sieve usage include the catalytic destruction of ozone and the adsorption of molecules like O_2 and N_2. It is conceivable that such side effects could be limited and that zeolites with specified cavity size could be produced in order to improve their selectivity. Linde Molecular sieves were available as:

- cylindrical pellets, 1/8 or 1/16 inch in diameter
- spherical pellets
- powder, 0.5 to 5 microns in diameter.

Their density ranges from 33 to 45 lb/ft^3. The voids amount to 45 percent by volume of the zeolites [Hersh 1961].

3.1.2.2 Precipitates

When it is not bound to reservoir molecules, the chlorine atom in the stratosphere will go on destroying ozone catalytically until it reaches the troposphere through washout and rainout mechanisms; however, it is possible that while in the stratosphere a chlorine atom (Cl) reacts with a methane molecule (CH_4) leading to the formation of a hydrochloric acid molecule (HCl) which renders the chlorine atom inoffensive. Such reactions could be favored by exposing stratospheric air to compounds which will bind the chlorine atoms or chlorine monoxides. Two major considerations constrain the release of such compounds in the stratosphere :

1. the side effects on the environment,
2. the destabilizing role of ultraviolet radiation.

3.2 DELIVERY SYSTEMS

Delivery systems may be either ground-based or airborne-based, and the latter type can be divided into two categories - lighter-than-air and heavier-than-air.

3.2.1 Ground-Based

Any ground-based delivery systems will depend on the atmospheric dynamics of Antarctica. The feasibility of ground-based operations is yet to be determined. One possible configuration is a thermal station (Figure 3.2) where "fixing agents", maybe gas-phase catalysts, are diffused into superheated air to rise up into the stratosphere via a 'thermal chimney.' These fixing agents bond to the ozone-destroying molecules such as the CFC's or the radical chlorine atoms to form a stable, non-reactive molecule that will eventually precipitate out of the atmosphere.

One possible support for a ground-based system comes from a dynamical theory of the ozone hole. That is, in early spring, when the sun hits the Antarctic continent, it warms the ozone-poor air in the troposphere to rise and displace the air in the stratosphere. A ground system may be able to utilize this rising of the air; for instance, a gas emission from the ground would potentially ride with the rising air to the stratosphere. Although there is usually little vertical transfer between the troposphere and the stratosphere, there is an instability period in the spring in which motion between the two layers occurs.

The rising of ground air, however, is atmospheric motion in a large scale, and there are possibly many arguments against the feasibility of a ground station, in particular the thermal chimney. First, the ozone hole is larger than the continent of Antarctica. With this magnitude, ground-based systems would have to be distributed throughout the continent. This may not only be geographically impossible, but also very expensive. In addition, the Antarctic atmosphere is very dry and very cold. Superheated air might diffuse and quickly come to a temperature equilibrium with the atmosphere or condense and fall at relatively low altitudes, never reaching the stratospheric layer of the atmosphere.

The theory of ground air warming in early spring and rising to the stratosphere still would have to be verified. If this theory does not hold, a ground-based system may not be feasible.

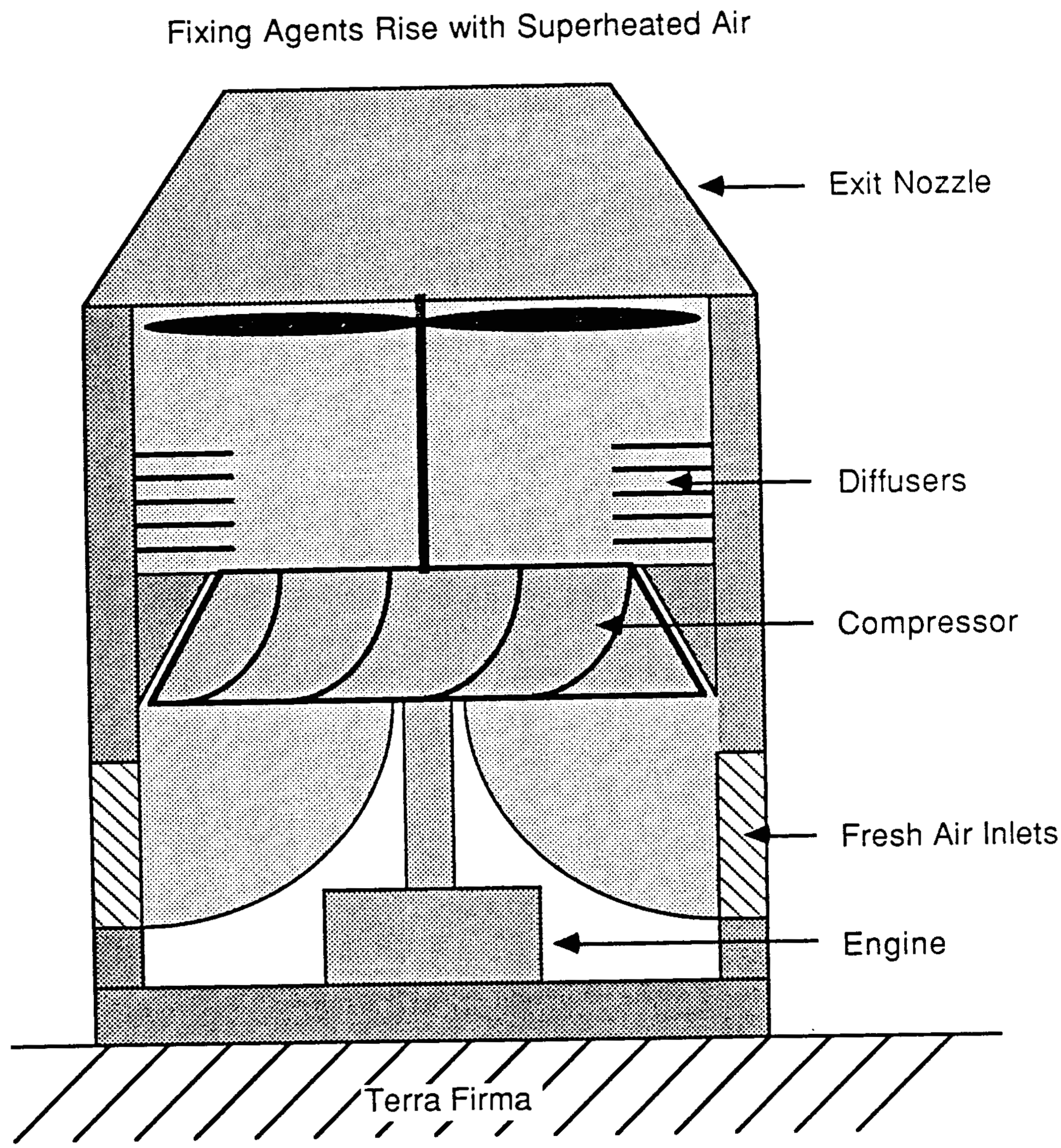


Figure 3.2 Ground Thermal Station

3.2.2 Lighter-Than-Air

Three types of lighter-than-air delivery systems were considered - dirigibles, aerostats, and balloons. Aerostats are tethered, non-mobile dirigibles, or more simply, tethered aerodynamic balloons (Figure 3.3). All of the systems that may be used for implementation aboard dirigibles would also work aboard either aerostats or balloons with a few changes that will be pointed out.

Dirigibles can be implemented as automated or semi-automated, self-contained, airborne factories. They would carry the replenishment or elimination system directly to the hole, and would generate the total power requirements for its operation. If the total weight of the combined dirigible and replenishment system were beyond the load capacity of any practical size dirigible, a hybrid airship could be employed. A hybrid airship combines the lifting capacities of a dirigible with those of a more ordinary aircraft such as helicopters (Figure 3.4). Hybrid airships are being developed for cargo hauling operations such as logging, where the airship carries its own unladen weight and the 'helicopters' lift the cargo. Hybrid airships also have the added benefit of being highly maneuverable. This characteristic may be desirable at high altitudes where strong winds are prevalent for adequate control to be maintained at all times.

3.2.3 Heavier-Than-Air

The two possible types of heavier-than-air delivery systems are airplanes and rockets. An airplane could function in the same manner as a dirigible. The replenishment or elimination system along with all power generation capabilities could be self-contained onboard the aircraft. A scenario being examined for short-duration aircraft would be the dispersal of fixing agents that would react with the chlorine reservoirs, or bond with chlorine radicals or the CFC molecules to form precipitates (Figure 3.5).

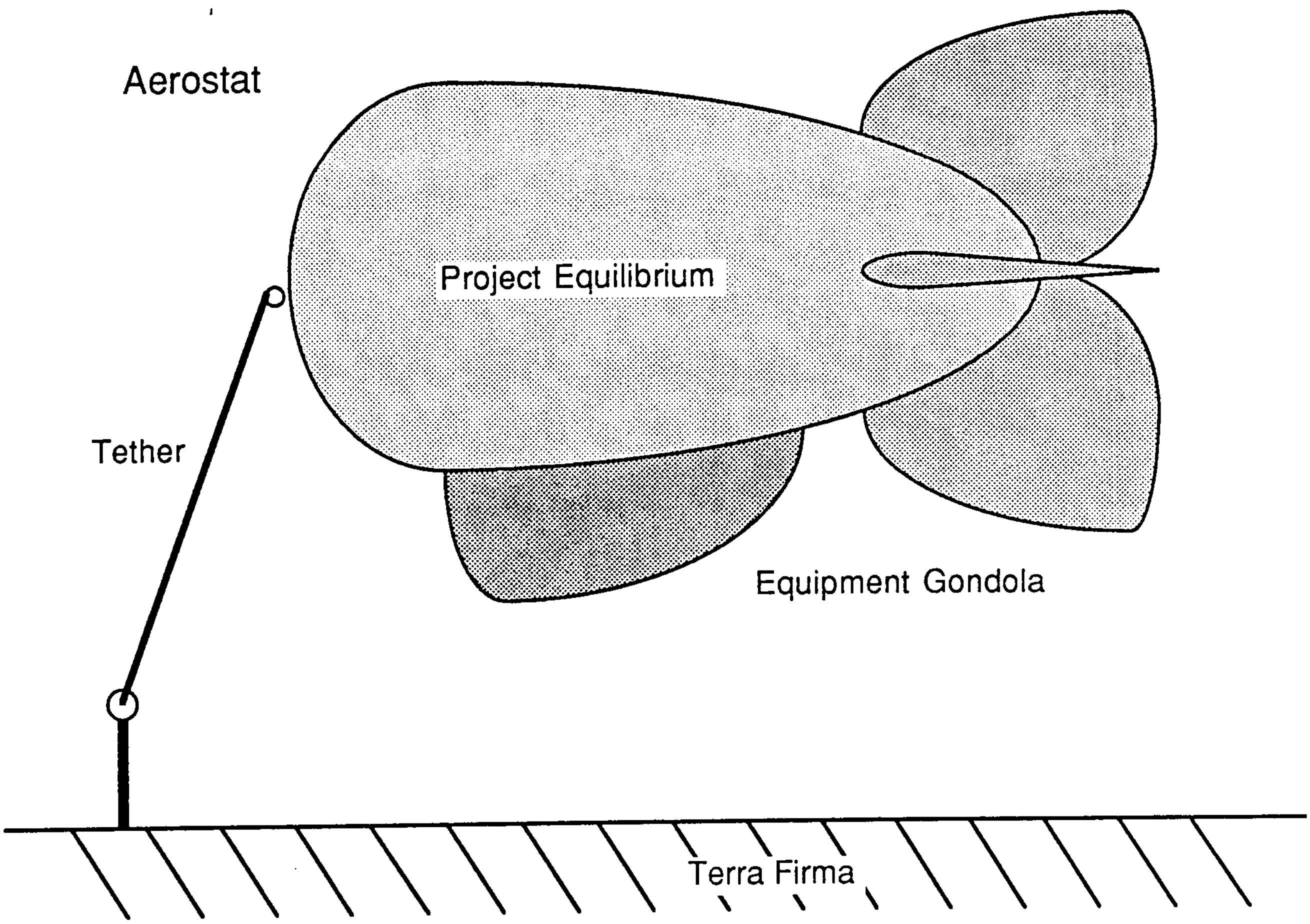


Figure 3.3 Aerostat

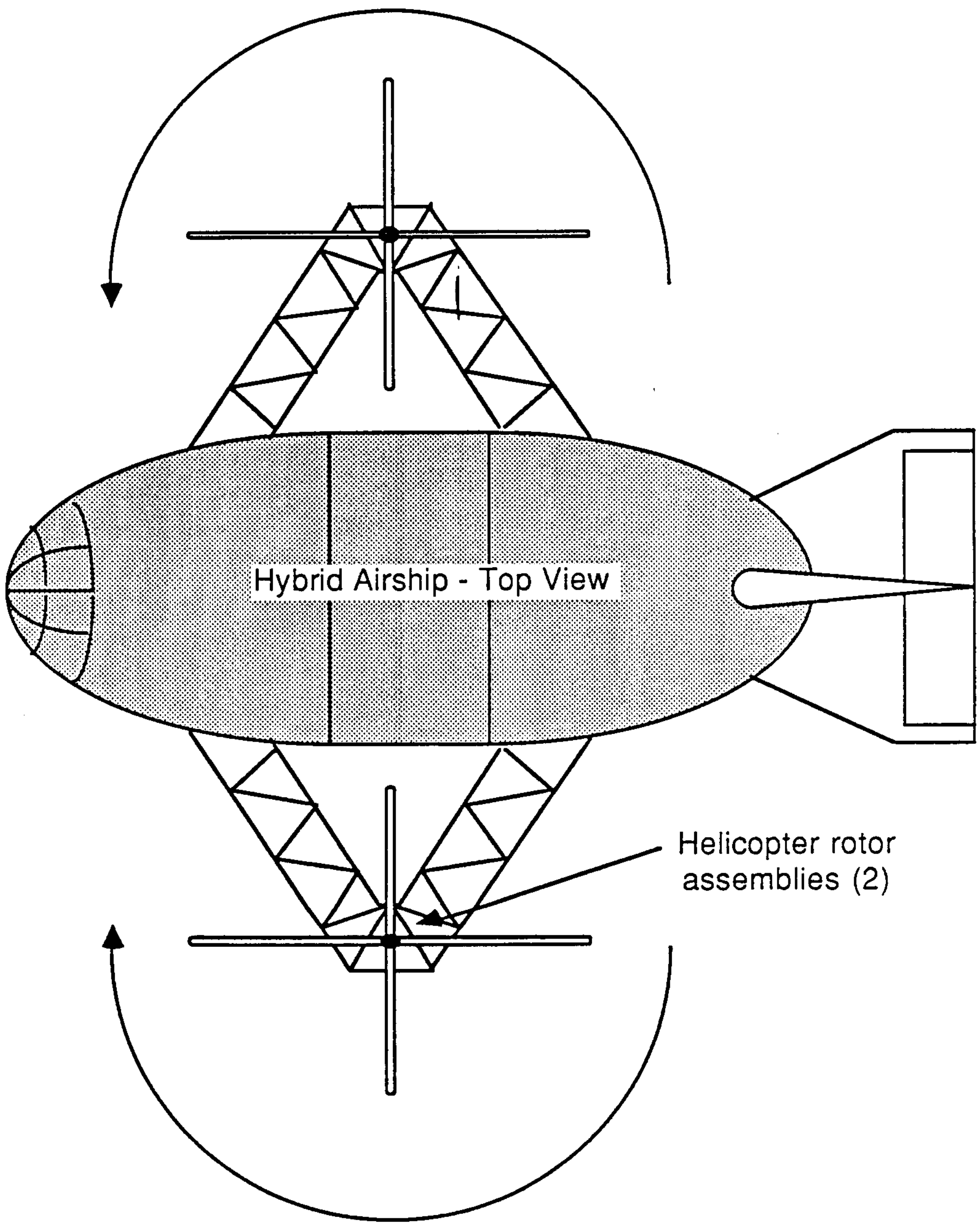
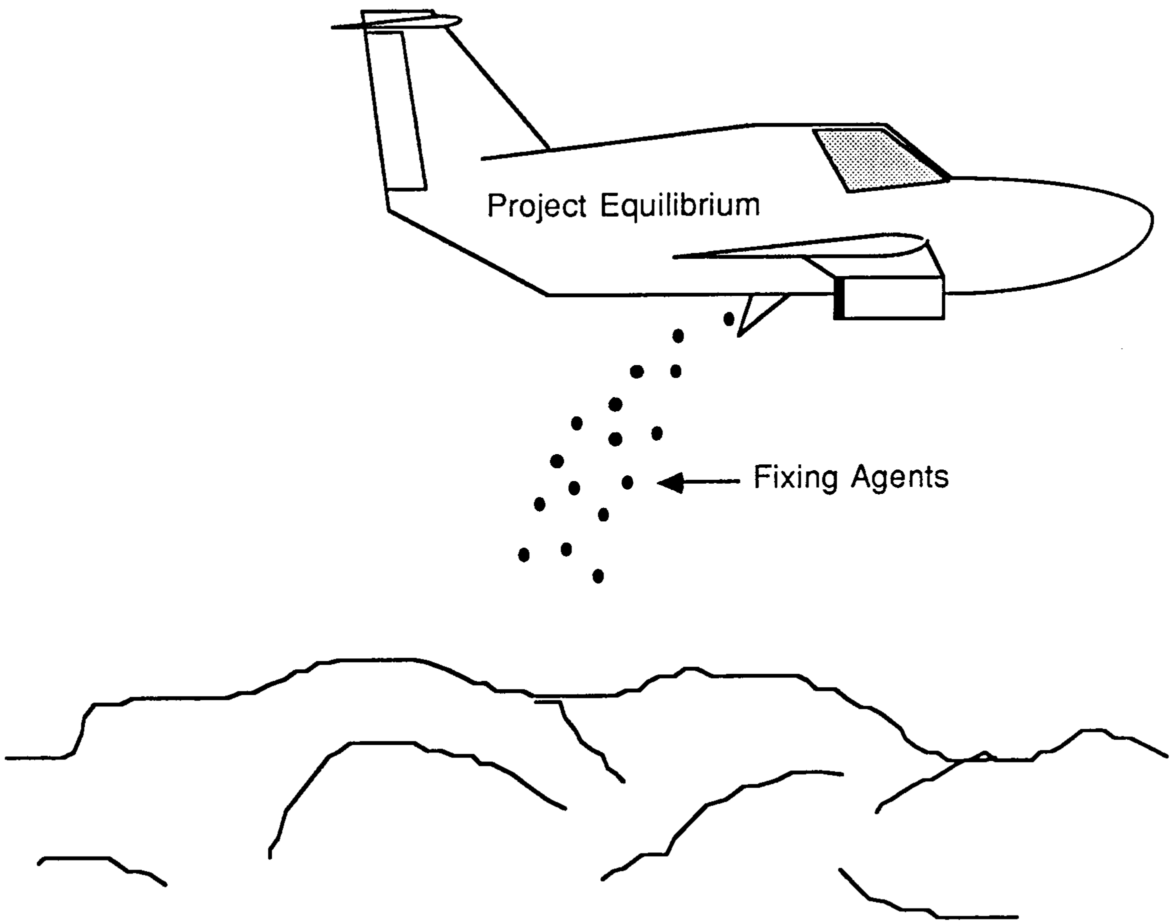


Figure 3.4 Hybrid Airship



Seeding of Stratospheric Clouds with Fixing Agents

Figure 3.5 Seeding by Airplane

3.3 POWER SYSTEMS

The following power systems were investigated: nuclear, chemical, wind, solar, and microwave. All of the systems or combinations thereof will have to supply the power requirements for both the replenishment and delivery systems.

3.3.1 Nuclear Power

Two existing nuclear power system designs were studied as samples. One was a design by Professor Francis Morse [Morse, 1966] and the other by General Electric [GE 1986]. Both have a weight of approximately 20 lb/hp (0.0268 lb/W) which includes both reactor and shield weight. *The Preliminary Design of a Very Large Pressure Airship for Civilian and Military Applications*, by T.A. Bockrath, had been done using Professor Morse's design weight for nuclear reactors. [Bockrath, 1983] The airship specifications with both diesel and nuclear propulsion systems are summarized in the following table.

Table 3.1 Very Large Pressure Airship

Design Specifications		
Cruise Speed	200 mph	
Range at Cruise Speed	12,000 miles	
Operating Altitude	2,000 ft	
Payload Capacity	5×10^6 lbs	
Propulsion Systems		
Power Required	250,000 hp (190 MW)	
	Diesel Option	**Nuclear Option**
System Weight	500,000 lbs	5×10^6 lbs
Fuel Weight	5.7×10^6 lbs	N/A
Cargo Capacity	5.1×10^6 lbs	6.3×10^6 lbs
Total Weight	18.9×10^6 lbs	18.9×10^6 lbs

Professor Morse and T.A. Bockrath demonstrate the feasibility of such a large airship for both commercial and military applications for long endurance missions. Their airship models could be adapted for use in Antarctica by using the data taken by Andrew S. Carten and George H. McPhetres who conducted aerostat operations in Arctic weather [Carten, 1983]. Their experiments centered on snow and ice buildup and removal. For a nuclear powered airship, the heat generated by the reactor could be used to heat the hull of the airship to prevent snow and ice buildup. Both Morse and Bockrath state that the psychological objections to nuclear-powered aircraft would have to be overcome. Frank E. Rom and Patrick M. Finnegan delve into the questions about the safety of nuclear-powered aircraft. They show that an aircraft can be designed such that in a worst case scenario of a direct impact by an airliner, no person would receive more radiation exposure than the Federal Radiation Council's limits.

3.3.2 Wind Power

Power requirements for a system may be supplemented by wind or solar power sources. The wind power system would essentially be a windmill and consist of a turbine and a power converting device.

Wind power is generally not very effective for a flying vehicle since it will be moving with the atmosphere, but it may be feasible on an aerostat which would be tethered to the ground. Wind power may be generated on the ground and be used to power a ground station or to be stored and transmitted to a flying vehicle.

The maximum power, P_m, that can be extracted from a given windstream is expressed as [Cheremisinoff, *Wind* , 1978]

$$P_m = (0.593)\ (\text{density of air})\ (\text{freestream velocity})^3\ (\text{area of turbine}) / 2.$$

At Cape Evans, the average August wind speed is about 15 knots (7.72 m/s). [Vowinckel, 1957] Estimating the density of air to be the standard atmospheric sea level density of 1.225 kg/m^3, the theoretical maximum power output per area of turbine would be about 0.17 kW/m^2. The size of the turbine and the number of windmills would be dictated by the power requirements. Predictable stable wind conditions are most desirable for a reliable wind generating system. Selecting suitable sites where wind variability and turbulent conditions are minimal may be difficult in Antarctica. Although summer conditions may be acceptable in certain locations, winter conditions with frequent blizzards and unpredictable gusts would make wind power generation almost impractical.

3.3.3 Solar Power

Solar power stations may be based on the ground, on the vehicle itself, or in space. For the ground-based or space-based stations, power would have to be transmitted to the operating vehicle.

If the major portion of the mission operations is to be conducted during spring time, ground-based solar generation will not be feasible because of low solar radiation reaching the south pole at that time. Summertime operations would be more viable, since the amount of radiation received at the surface of Antarctica in the summer is greater than the summertime amounts over the lower latitudes. Solar power generation from the vehicle would have similar constraints. A space-based system would be more flexible. Since an essential part of the solar satellite power station is microwave transmission, it is described further under Microwave Power.

Although the amount of solar radiation reaching the surface in the summer is significant, solar energy systems, whether they be thermal or photovoltaic, are characterized by extremely low efficiency in the conversion of solar energy into electricity. Systems using photovoltaic cells usually have a conversion efficiency of about 15 percent, and a typical output for a silicon p-n junction cell is about 10 W/ft^2 (0.1 kW/m^2). [Cheremisinoff, *Solar* , 1978]

3.3.4 Microwave Power

Microwave power configuration consists of beaming microwave beams from either a ground station or a satellite to power a flying vehicle. Research and experiments have been conducted on both types of configuration.

The ground configuration has been tested on a prototype built by Joe Schlesak of the Canadian Communications Research Center. The general configuration consists of generators about the size of telephone booths which pump electricity into a dish-shaped antenna, also stationed on the ground. The electricity is then beamed upward, as microwave energy, to rectennas or rectifying antennas mounted on the underside of the airplane. The rectennas convert the microwaves back to electricity to power the airplane. [Rogers, 1987] For the test of the prototype, 10,000 W of microwave energy was beamed to copper receptors which converted microwave beam to 150 W of direct current to power the propeller on the airplane. [Gray, 1987]

A satellite-based configuration, called Satellite Solar Power Station, had been studied extensively by NASA. This design consisted of two, large, solar cell-filled collection surfaces of about 11 mi^2 each on a geosynchronous satellite. These panels would be capable of producing 8,500 MW of electricity to a microwave transmitting antenna. The antenna would then convert the electricity to microwave radiation and beam it down to a receiving antenna. It was predicted that 5,000 of the original 8,500 MW will be received on the surface of the earth. A ground experiment was performed by NASA in 1975 to prove the feasibility of the concept. For a transmitting antenna and a receiving antenna placed one mile apart, a conversion efficiency of 82% was achieved [Cheremisinoff, *Solar*, 1978].

Powering the vehicle with microwave beams will significantly reduce the weight of the vehicle. Also, the vehicle has the potential of staying up in the air indefinitely. The concept of microwave-powered vehicles, however, is relatively new, and the associated technology requires further development. In addition, environmental concerns still remain. Critics claim that exposure to low levels of microwaves increases the chances of cancer, especially for people living near microwave communication antennas. For the satellite-based system, there is also the question of how the atmosphere will be perturbed, especially how the ozone depletion process will be affected, by microwaves.

3.4 SUPPORT SYSTEMS

Support systems include any required ground stations, vehicle navigation systems, and weather and ozone monitoring facilities. These will essentially complete the infrastructure for the operation of stopping the depletion of ozone.

Ground stations may consist of runways, launch pads, and personnel and maintenance facilities. Where these ground stations can be located would have to be determined. A possible retreat for the mission is Punta Arenas, a city in the southern tip of South America, close to the Palmer Peninsula of Antarctica. This city has a commercial airport with three large runways which accommodated NASA's research planes ER-2 and DC-8 in the 1987 Airborne Antarctic Ozone Experiment. On the continent of Antarctica itself there are many research stations operated by different countries. Most of these stations are located near the coast. One of the major U.S. stations with air facilities is Williams Air Operation Facility in McMurdo Sound. Depending on the number of air vehicles required, construction of additional air facilities may have to be considered.

Vehicle navigation systems will be an important element in the infrastructure since most of the operations will probably be unmanned. Part of the navigation system will consist of a satellite network, like the Global Positioning System (GPS) satellite network.

The full GPS constellation, expected to be completed by mid 1990, would consist of 18 satellites and 3 spares in 6 orbital planes in 12-hour circular orbits. GPS is designed to provide precise position, velocity, and time data of a user station.

Finally, weather and ozone monitoring facilities will be essential in determining the schedule of operation. Redundant and reliable systems should be employed in measuring weather and ozone data. Various ozone measuring techniques are in use currently. They include ground-based Dobson instruments, in-situ balloon-borne and airborne instruments, and satellite instruments. Dobson instruments are ultraviolet spectrometers used to compare the absorption by ozone at different wavelengths. A special application of the Dobson instrument is the Umkehr technique, which consists of following the sun as it crosses the sky and measuring the variation in absorption of the ultraviolet radiation to obtain the ozone variations with altitude. In-situ instruments, on the other hand, examine the chemistry of the air through which they travel. A common instrument used on balloons is an ozonesonde, which is an electrochemical ozone analyzer. [Kerr, 1987]

Remote sensing of ozone from a satellite is usually done with the Solar Backscatter Ultraviolet (SBUV) instrument. SBUV measures the amount of solar radiation scattered up from the atmosphere and compares it with the amount coming from the sun. Since ozone absorbs radiation of different wavelengths in varying degrees, measurement is taken at different wavelengths to determine the amount of ozone in the atmosphere. If the amount of radiation at the absorbed wavelengths increases with respect to the amount at the unabsorbed wavelenghts, the amount of ozone has decreased. On the other hand, if the radiation at the absorbed wavelengths decreases, ozone has increased. [Stolarski, 1988] One problem that has been sited with the SBUV is its inability to maintain a constant sensitivity to ozone because of the deterioration of the diffuser plate that directs incoming sunlight into the instrument. [Kerr, 1987]

4. FUTURE WORK

Having gained some understanding of the problem and some insight into possible methods of solution, this group has identifed many unknowns that require further study. This section outlines some of these unknowns and recommendations for future work. It is stated at the outset that in no way are the experiments or studies suggested here comprehensive; more unknowns are sure to surface as more information is collected. Furthermore, some of experiments listed below may already have been conducted or are being conducted currently which this group is not aware of; that is, answers to some of the questions may already exist which are not known to this group.

There are three basic areas of unknowns: the nature of the ozone hole, mechanisms for stopping depletion of ozone, and implementation of these mechanisms. Listed below are some of the questions identified by this group. Following each set of questions is a summary of the background information already detailed in the previous sections and of suggested experiments.

4.1 MORE ON THE OZONE HOLE

Much research is being conducted currently to determine the exact cause of the ozone depletion and of the ozone hole. One of the recent experiments conducted was the 1987 Airborne Antarctic Ozone Experiment. This experiment, which used ground- and satellite-based measuring devices, balloons, and airborne laboratories, determined that the ozone hole was at its largest in 1987. [Stolarski 1988] Preliminary results from the experiment support the CFC theory. Formal reports will not be released until May 1988.

Question: **What state of the ozone hole is critical? What are the effects of the ozone decrease? When do we act?**

Background: Although there is little vegetation, there are penguins, seals, and other marine life which may be critical to the food chain. Effects of increased exposure to ultraviolet radiation on these Antarctic life are yet unknown, but studies are being conducted currently by biologists like Deneb Karentz of the University of California, San Francisco's laboratory of radiobiology and environmental health. [Zurer, *Antarctic...*, 1987]

Global ozone decreases as well as the effects of such decreases should also be firmly established. Determining the critical level of ozone over Antarctica as well as over the entire earth is important in laying out the "plan of action" for the stopping of ozone depletion.

Experiment: Further experiments are necessary to determine the exact cause of the hole. In addition, small scale experiments to test theories on specific dynamical and chemical conditions may be conducted. Computer simulations based on findings from these experiments would help predict the future state of the ozone hole and provide a basis for a plan of action.

Question: How does the washout process occur? Can it be accelerated?

Background: A chlorine atom in the stratosphere switches back and forth between temporary reservoirs and the destructive chlorine monoxide chain reaction. Rowland estimated that each chlorine atom can destroy about 100,000 molecules of ozone in its lifetime. The destructive cycle ends when one of the reservoir molecules diffuses down to the troposphere and is removed by rain. This process is called the washout.

Experiment: An experiment should be conducted to determine how a chlorine atom or a chlorine compound is removed from its ozone destroying cycle in the washout process. Further study into the dynamics and chemistry of the Antarctic atmosphere is required in order to develop and test possible theories on the washout process.

Question: Can extra odd nitrogen molecules shift the equilibrium away from chlorine monoxide to chlorine nitrate, one of the chlorine reservoirs?

Background: Observations from the 1987 Airborne Antarctic Ozone experiment, as well as the 1986 ground-based experiments, indicate that the abundance of vapor-phase odd nitrogen, which forms the chlorine nitrate compound, is extremely low within the ozone hole. Several scientists have proposed that the polar stratospheric clouds (PSC's) contain condensed nitric acid, hydrochloric acid, or both. This would explain how an odd nitrogen molecule can be inhibited from combining with chlorine monoxide to form a reservoir. This would lead to an abundance of active chlorine that are free to destroy ozone.

Although odd nitrogens are critical in forming the reservoir molecules, they also destroy ozone catalytically as shown by the following equations:

$$NO_2 + O \Rightarrow NO + O_2$$
$$NO_2 + h\nu \Rightarrow NO + O$$
$$NO + O_3 \Rightarrow NO_2 + O_2$$

where hν is ultraviolet radiation. So there are potentially two competing reactions involving odd nitrogens.

Experiment: A laboratory experiment may be conducted to determine which of the two competing reactions - one forming chlorine nitrate and the other destroying ozone - would prevail. The conditions over Antarctica must be carefully simulated in studying the kinetics of the two reactions.

Question: **Are there any reservoir molecules which are stable under ultraviolet radiation and not susceptible to the heterogeneous reaction of the polar stratospheric clouds?**

Background: Solar radiation is a very destabilizing element. Although in winter and in early spring, sunlight reaching the area of the ozone hole is not strong enough for dissociation of reservoir molecules, as the amount of sunlight increases, they become vulnerable.

In addition to ultraviolet radiation, reservoir molecules can be destroyed by certain molecules such water as well as another reservoir molecule of a different species. The reactions are illustrated below:

$$H_2O + ClONO_2 \Rightarrow HNO_3 + HOCl$$
$$HCl + ClONO_2 \Rightarrow HNO_3 + Cl_2$$

Formation of reservoir molecules are also inhibited by polar stratospheric clouds which fix or freeze the potential molecules which form the reservoir.

Experiment: Laboratory experiments to determine the kinetics of the reservoir reaction and how to affect them are recommended. Quantitative studies of the PSC heterogeneous reaction should be made. The atmospheric conditions over Antarctica should be better understood including the polar vortex, the frigid temperatures, and the polar stratospheric clouds (PSC). An experiment that can simulate the heterogeneous reaction on the surface of PSC and that can quantify the reaction would reveal much about the process of reservoir formation and inhibition.

4.2 MORE ON THE MECHANISMS

In determining feasible mechanisms for stopping the depletion of ozone, extensive chemistry research is required. Questions about precipitates, photocatalysis, and molecular sieves are numerous.

Question: **Can molecular sieves that do not destroy ozone be produced? How difficult is it to custom-make the sieves to adsorb only certain molecules? In what form should the molecular sieves be used (pellets, powders, or others)?**

Background: Some side effects of molecular sieves used in industry are catalytic destruction of ozone and adsorption of certain molecules including oxygen and nitrogen. The selectivity of the sieves may be improved to limit these side effects. Molecules that need to be adsorbed include chlorine, chlorine monoxide, chlorine nitrate (reservoir) and chlorofluorocarbon. Molecular sieves produced by Linde Company were available as cylindrical pellets, spherical pellets, and powders.

Experiment: Laboratory experiments can be conducted to fabricate possible molecular sieves and determine which is most effective in adsorbing unwanted molecules but not in destroying ozone. In-situ experiments on either a balloon or an airplane can also be performed to test the feasibility of using molecular sieves and their possible configurations.

Question: **How much ozone can be sacrificed in the process of stopping more destruction of ozone?**

Background: Because ozone is such an unstable molecule, it will be vulnerable to any mechanism. Therefore, it will be virtually impossible to devise a mechanism that would be ozone-safe All methods would involve two competing reactions - one that destroys ozone and one that inhibits or removes the ozone-destroying element. Sacrificing some ozone molecules in order to incapacitate one chlorine atom may be acceptable, since one chlorine atom can destroy up to 100,000 ozone molecules.

Experiment: Computer simulations of various methods for stopping the ozone depletion can be performed to determine the rates of the two competing reactions. If the reaction that removes the ozone-destroying element is more favorable indicating a positive shift in equilibrium, then the corresponding method may be an acceptable one.

4.3 MORE ON IMPLEMENTATION

Implementation techniques will depend greatly on the meteorological conditions of Antarctica. Although most of the methods will probably be unmanned and remote controlled, human interaction at certain levels of operation will surely be required. The level and the conditions of human involvement must be clearly defined.

Question: When is the best time to operate a flying vehicle?

Background: Four factors to consider are

1) cold temperature,
2) high winds and wind shear,
3) mechanism to be employed, and
4) amount of ultraviolet radiation.

The last two categories are related in that the type of mechanism to be used depends on the amount of solar radiation. For instance, if molecular sieves are to be used to adsorb chlorine nitrate reservoirs, then the operation should be conducted in early spring before too much ultraviolet radiation can disassociate these molecules.

For flying conditions only, summer is probably the best time because of the calmer winds and the higher temperatures.

Experiment: Studies need to be made which assess the acceptable flying conditions for each type of vehicle (e.g. blimp or airplane) and for each mechanism.

Question: Because of the destructive effect of gas exhausts on ozone, what scale of operation is acceptable for flying vehicles like chemically powered airplanes?

Background: Common exhaust products for chemically powered vehicle are water and nitrogen oxides. Both destroy ozone catalytically as shown by the following reactions:

$$H_2O + O \Rightarrow 2OH$$
$$OH + O_3 \Rightarrow HO_2 + O_2$$
$$HO_2 + O_3 \Rightarrow OH + 2O_2$$

Experiments: Laboratory experiments and computer simulations may be conducted to determine the magnitude of exhaust effects.

Question: Can a ground-based system be feasible?

Background: Two types of ground-based configuration, passive and active, were identified earlier. A passive configuration involves emitting gaseous chemicals (e.g. chlorine binding agents) and allowing them to ride with the rising air in the spring. The rising spring air is based on a theory which states that in early spring, solar radiation reaches the Antarctic continent and warms the tropospheric air which rises to the stratospheric levels displacing the air there. This theory is one of the dynamic theories proposed to explain the ozone hole.

A possible active configuration is a "thermal chimney." This involves injecting superheated air carrying binding agents into the atmosphere. Given enough momentum and ideal meteorological conditions, the hot air may reach the stratospheric levels.

Certain factors point against a ground-based system: large size of the hole, very cold temperatures, and very dry atmospheric conditions. Because the hole is larger than the continent of Antarctica, it will be difficult to distribute enough ground-based systems to significantly affect the hole. Furthermore, the fluid dynamics of superheated air in cold, dry environment is not very well known.

Experiment: Laboratory experiments and computer modeling can be done to determine the fluid motion of heated air in a cold, dry environment. In addition, further experiments to verify the theory of ground air warming in the spring and rising to the stratospheric level should be conducted.

4.4 General

The questions in this section are general in nature and no experiments are proposed. They are questions which need to be addressed, however.

<u>Question</u>: **Would there be enough time to develop any new technology if the problem needs to be solved now, and if not, can it be solved with existing technology?**

<u>Background</u>: At the present, the exact cause and effect of ozone depletion are still being sought. It is not known if and when the ozone hole would be critical. In developing possible strategies for the solution to the problem, the technology required would have to be assessed. For instance, among the possible configurations suggested in this report, high-altitude airplanes and dirigibles still need development. Microwave power seems quite feasible, but it too is a relatively new technology.

<u>Question</u>: **What are the environmental effects of any of the systems used?**

<u>Background</u>: Any attempts to stop the depletion of ozone should not lead to another environmental problem which is more serious than the original problem. Side effects of any implementation should be carefully assessed.

5. CONCLUSIONS

Project Equilibrium has provided an initial analysis of possibilities for stopping the depletion of ozone over the South Pole, but this group has barely scratched the surface. Clearly, more in-depth studies are required from many fields of expertise such as chemistry, meteorology, fluid dynamics, and aeronautics to name just a few.

Presently, the ozone hole is not considered critical, and the conditions for a critical state have not yet been firmly established. The ozone hole may not prove to be a problem at all after further research is conducted into the nature of ozone depletion and its global implications. Results from the 1987 Airborne Antarctic Ozone Experiment will surely shed some light. However, uncertainty about the problem should not preclude a thorough study into possible solutions now.

At the 1986 workshop on Current Issues in Atmospheric Change, held at the National Academy of Sciences, the nature and the consequences of increasing number of atmospheric trace gases such as carbon dioxide and chlorofluorocarbon were reviewed. The workshop participants have concluded that

> ...steps should be taken now to slow emissions or mitigate the potential impacts of the rising atmospheric trace gases discussed in the workshop.
> ...a thorough study of the impacts of and appropriate responses to rising atmospheric trace gases is among the most pressing issues on the national research agenda.

Members of Project Equilibrium want to stress that in taking steps to solve the problem of ozone depletion, the most thorough research must be conducted to ensure that any secondary effects of those steps on the environment are minimal.

It is the hope of this group that the study presented in this report will inspire other more thorough studies into solving the potentially critical problem of ozone depletion.

6. MANAGEMENT AND COST STATUS

6.1 MANAGEMENT REVIEW

Three people were involved with Project Equilibrium. Since project inception, the group was organized as shown in Figure 6.1.

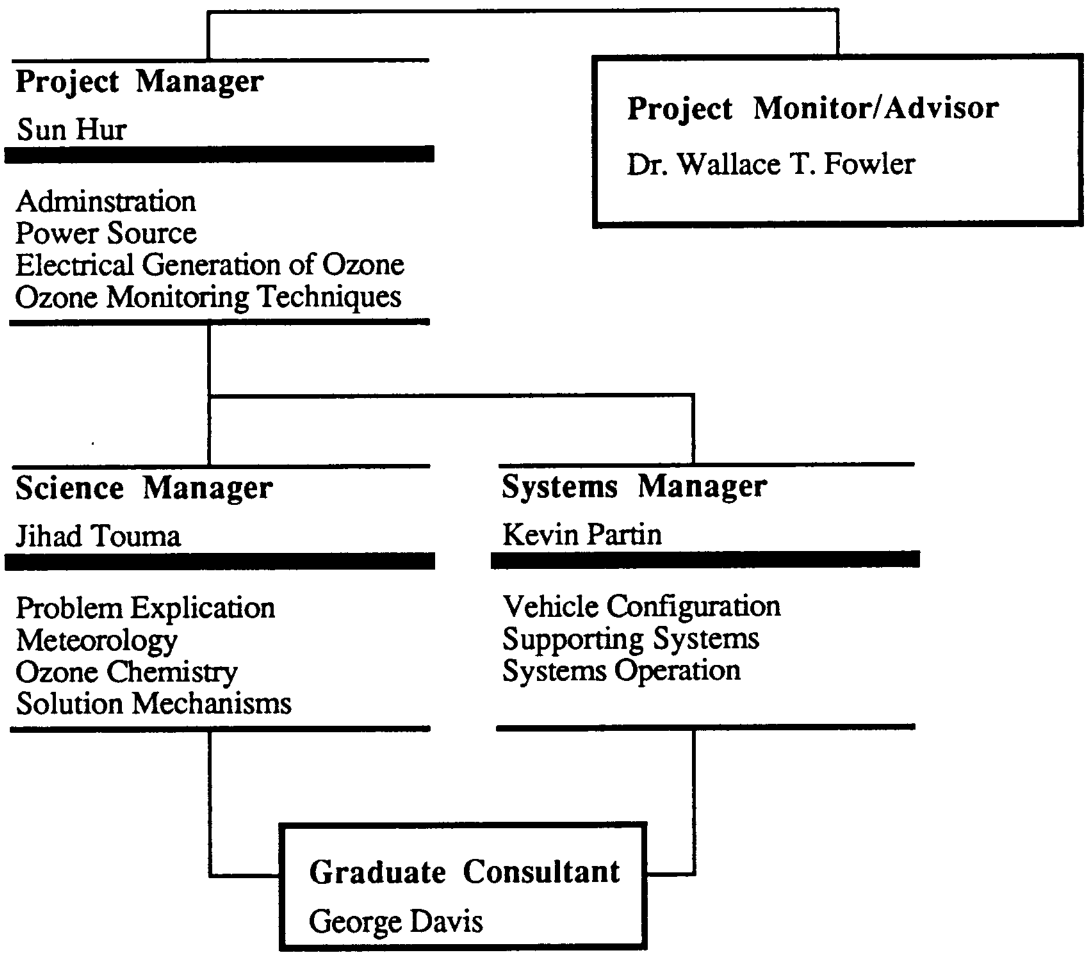


Figure 6.1 Group Organization

The group was headed by the project manager who coordinated the study and who served as the single point of contact with the project monitor. All technical tasks were divided among the three members with the project manager overseeing all tasks.

6.2 MANAGEMENT SUMMARY

Although the major goals of the study were achieved, there were many problems associated with the management structure. First, because the group was small, each member had to carry a large workload. So if one member was not able to complete his assigned task, it significantly increased the amount of work for the other members. The group also had a misconception about its flexibility. The small size actually made the group somewhat inflexible because there were not enough people to adequately absorb uncompleted work.

For a small group to function well, compatibility of the members is important. At times, the members of this group had different ideas on how to attack a particular problem or on the specific objectives of a particular area of the study. Personality differences also made timely completion of work difficult. In spite of its small size, the group faced communication problems as well; it was difficult to set up meetings with all members present.

In general, the group did not have a clear enough idea on the scope of the project - How detailed should the study be? To what extent should the study be carried through? If the problem to be investigated were better understood, the scope of the study could have been better defined.

Despite the managerial problems discussed above, the major goals of the project were accomplished. Participating in this project did provide invaluable technical and management experience for all members of the group.

6.3 COST STATUS

The 16-week cumulative personnel costs are summarized in Table 6.1. The hourly wages are as specified in the Proposal.

Table 6.1 Cumulative Personnel Costs

Personnel	Hourly Wage	16-Week Hours	16-Week Salary
Project Manager	$ 25.00	269.5	$ 6,737.50
Science Manager	22.00	129.5	2,849.00
Systems Manager	22.00	175.0	3,850.00
Consulting	75.00	10.0	750.00
Total for 16 Weeks			$ 14,186.50
Estimated 16-Week Total			$15,664.00
Percent of Estimated Cost Used			91%

The 16-week cumulative material and hardware costs are summarized in Table 6.2. Since this study required no computational work, major costs were incurred in the use of personal computers and in documentation.

Table 6.2 Cumulative Material/Hardware Costs

Material/Hardware	16 Week Total
Computer & Software	$ 2,250.00
Photocopies & Transparencies	153.47
Travel Expenses	5.00
Actual Total for 16 Weeks	$ 2,408.47
Estimated 16-Week Total	$ 3,217.50
Percent of Estimated Cost Used	75%

A comparison of the actual total project cost to the estimated total is shown below:

Actual Total Project Cost for 16 Weeks	$ 16,594.97
Estimated Total Project Cost for 16-Weeks	18,881.00
Percent of Estimated Total Project Cost Used	88%

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APPENDIX

A. LIST OF ACRONYMS

CFC - chlorofluorocarbon

PSC - polar stratospheric clouds

NASA - National Aeronautics and Space Administration

APPENDIX B

PROPOSAL

A PROPOSAL
FOR A FEASIBILITY STUDY
OF AN OZONE REPLENISHMENT SYSTEM

Written in Response to:

RFP #ASE 274L

Submitted to:

Dr. Wallace T. Fowler

The University of Texas at Austin
Department of Aerospace Engineering
and Engineering Mechanics

Presented by:

Project Equilibrium
The University of Texas at Austin

March 25, 1988

EXECUTIVE OVERVIEW

Presented here by Project Equilibrium is a proposal for a feasibility study of an ozone replenishment system. The focus of the study is the Antarctic ozone hole - the area of ozone depletion over the South Pole. The objectives of the study are to develop an "engineer's understanding" of the problem, propose candidate solutions, and propose experiments that may elucidate unknowns and problems associated with the candidate solutions. The results from this study will hopefully assist future work on this problem.

The study will be based on one basic assumption - that a major factor in the depletion of ozone is the chlorine atom released from chlorofluorocarbon molecules. Four mechanisms of ozone replenishment have been identified so far: precipitation, molecular sieves, photocatalysis, and electrical discharge. These methods will be analyzed further, and other mechanisms will be investigated. Implementation of these methods with either a flying system or a ground-based system will be examined. Design requirements such as power source, supporting systems, and operations will be considered for all candidate solutions. Additional assumptions may have to be made for each solution.

To demonstrate that the contract can be successfully fulfilled, a program schedule and the project cost estimate are given at the end of this proposal.

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LIST OF ILLUSTRATIONS

1 GENERAL SUMMARY

This document is in response to Request for Proposal (RFP) #274L for an ozone replenishment system. It outlines how Project Equilibrium will satisfy the design specifications given in the RFP. This document is divided into four main sections: general summary, technical proposal, management proposal, and cost proposal. The general summary gives an overview of the problems and objectives of the design study. The technical proposal contains descriptions of what the project intends to deliver at the end of the contract. The management and cost proposals describe organizational structure, program schedule, and cost estimates for the fulfillment of the contract.

1.1 PROJECT BACKGROUND

Recent findings have confirmed that the springtime amounts of ozone over the South Pole have decreased by over 40 percent since 1977. The area of ozone depletion is about the size of the United States and extends roughly from 12 to 24 kilometers in altitude in the stratosphere. Although such a hole is unique to the atmosphere over Antarctica, an average ozone loss of about 5 percent during the past nine years has been observed globally.

Ozone makes up less than one part-per-million of the atmospheric constituents, but absorbs most of the dangerous ultraviolet radiation which would otherwise reach the earth. This radiation can cause very harmful biological effects including human skin cancer, cataracts, immune deficiencies, and damage to crops and aquatic ecosystems.

One of many theories proposed to explain the ozone depletion is contamination of the stratosphere by certain man-made chemicals, especially chlorofluorocarbons (CFC). CFC's are found in such everyday items as styrofoam and freon. These molecules are very stable in the lower atmosphere; however, the radiation levels at higher altitudes breaks down the CFC molecule releasing chlorine atoms which attack ozone viciously. Recent findings from the 1987 Airborne Antarctic Ozone Experiment strongly support this theory. A disturbing fact is that these molecules have a lifetime of about 100 years in the atmosphere, so ozone destruction will persist for many more decades even if all CFC use were to stop today.

One obvious line of attack to this problem is to reduce the amount of CFC usage and its release into the atmosphere. This however, does not eliminate the problem for many more years as discussed above. Are there other ways of solving the ozone depletion problem? This is the main question which Project Equilibrium will address in its study.

1.2 OBJECTIVE

The objective of this study proposed by Project Equilibrium is to determine whether or not there are any feasible methods of ozone replenishment over the South Pole. Although the general problem of ozone depletion may be global, the study will focus on the Antarctic ozone hole from an engineering standpoint only. In this study, ozone replenishment encompasses both direct and indirect methods of restabilizing the ozone concentration over the South Pole. Direct methods consist of creation of ozone. Indirect methods consist of elimination of ozone-destroying agents.

Three basic goals are to be achieved. They are

1. to develop an "engineer's understanding" of the problem of ozone depletion over the South Pole,
2. to propose candidate solutions to the problem, and
3. to propose experiments which may help differentiate the candidate solutions and identify unknowns and problems associated with their design.

These goals are described in more detail in the technical proposal. The final product of the study will not be a detailed presentation of just one or two best designs, but a proposal for several possible designs which will need detailed design studies by future research groups to determine which, if any, are truly viable.

2 TECHNICAL PROPOSAL

This section explains the three basic goals of Project Equilibrium named under Objective (Section 1.2).

2.1 UNDERSTANDING THE PROBLEM

2.1.1 The Ozone Hole

Ozone is a three atom modification (O_3) of the molecular oxygen (O_2). It plays a critical role in balancing the surface radiation levels on the earth. Ozone absorbs ultraviolet radiation in the upper atmosphere and converts it to heat. In natural atmospheric conditions, ozone is in a dynamic equilibrium, where the rate of its formation is equal to the rate of its destruction by the ultraviolet radiation.

In May 1985, the British Antarctic Survey team announced that the springtime amounts of ozone in the atmosphere over Halley Bay, Antarctica, had decreased by more than 40 percent between 1977 and 1984. The report was soon confirmed by other groups and showed that the region of ozone depletion was wider than the continent and that it extended roughly from 12 to 24 kilometers in altitude. Essentially, there was an ozone hole in the polar atmosphere.

2.1.2 Theories

As understood from current literature, three types of theories have been proposed to explain the ozone hole.

One is a chemical response to the solar cycle. NASA scientists postulated that the hole formation is in response to peaking of the 11-year solar sunspot. This theory did not hold up because violent solar activity on the surface of the sun peaked three times (1958, 1969, 1980) during the Halley Bay measurements; however, low ozone levels were reported during the 1980 peak only. Furthermore, high concentrations of nitrogen oxides predicted by the theory were not observed.

Other scientists focused on meteorological causes which would simply redistribute ozone without destroying it. They claim that peculiarities of Antarctic meteorology such as the polar vortex, impede the ozone rich air of the equator from reaching farther south until late in the Antarctic spring when the vortex breaks up with the warming of the atmosphere. Support for this theory could come from analysis of temperature distribution in the Antarctic region. If the springtime circulation is not able to reach the polar region one would expect to find a decrease both in temperature and ozone there. Although no significant temperature changes have observed during the period of hole formation, reports by the 1987 Airborne Antarctic Ozone Experiment pointed to a dramatic decrease in ozone level over a large area in one day. Such a dramatic change can best be explained with the air movement theory.

A third theory links the ozone loss with the rapidly increasing concentrations of chlorofluorocarbons CFC-11 and CFC-12 in the atmosphere. When these CFC molecules reach the stratosphere, they release a chlorine atom after absorbing photons. A chlorine atom is then involved in a chain reaction through which it destroys up to 100,000 ozone molecules before descending down to the troposphere and eventually precipitating to earth. This catalytic cycle does not operate unfettered.

Two kinds of reactions are believed to interfere with ozone destruction. One of them leads to formation of ozone when the chlorine monoxide reacts with nitrogen oxides. The other leads to the combination of a chlorine atom or a chlorine monoxide radical with another molecule to form a stable product that temporarily acts as a chlorine 'reservoir.' Eventually, however, such reservoirs absorb a photon or react with other chemicals, break apart and free the chlorine atom which resumes its catalytic cycle. That these retarding mechanisms are relatively ineffective over the Antarctic may be explained by the role the stratospheric polar clouds play in fixing or freezing the 'reservoir' molecules.

2.1.3 Further Research

With evidence supporting the last two theories, the solar-cycle theory seems to have fallen out of favor. The second theory, which involves natural meteorological causes, is beyond the scope of this study. Therefore, this study will focus on the third theory and assume that the major cause of ozone depletion over the South Pole is the chlorine atom which is released from chlorofluorocarbons in the stratosphere.

Further research will be conducted regarding this theory, since implementation of any proposed solutions will require increased understanding of the Antarctic atmosphere, circulation patterns, temperature and pressure variations. These considerations will be especially important in determining the period of operation of the ozone replenishment system; however, obtaining current, accurate information will be difficult. Additional assumptions regarding the problem may have to be made as candidate solutions are proposed and analyzed.

2.2 CANDIDATE SOLUTIONS

This section is divided into two parts: ozone replenishment mechanisms and implementation. The first part describes some of the methods for ozone replenishment that have already been identified. The second part outlines the essential elements that will be considered in designing the system of implementation.

2.2.1 Ozone Replenishment Mechanisms

There are two basic methods of ozone replenishment - direct and indirect. The direct method is to actively create ozone to make up for the depletion. The indirect method is to eliminate those agents which are destroying ozone.

Based on the assumption that chlorofluorocarbons are a major factor in ozone depletion, four possible mechanisms of ozone replenishment have been suggested so far.

First, photocatalysts, which would enhance the formation of ozone molecules, may be spread in the stratosphere with the objective of establishing a new dynamic equilibrium of ozone formation and destruction.

Second, ozone molecules may be produced by electric discharge. Already established industrial processes may be accommodated for use in flight.

Third, chlorine atoms may be precipitated by getting them to react with binding molecules. These molecules will have to react selectively with chlorine atoms. Furthermore, the precipitate must not harm the environment, otherwise it must be collected.

Fourth, molecular sieves with affinity to chlorine atoms or compounds may be used to remove the destructive chemicals from the stratosphere. The existence of such sieves and their usage are to be determined.

Other methods will be investigated. As more information about these methods and the ozone problem is acquired, some of these methods may be discarded.

2.2.2 Implementation

This study proposes to investigate all candidate delivery-methods for the ozone replenishment system. Flying and ground-based systems shall be explored.

The flying-system designs shall include the following:

1. Definition and sizing of the power source for the vehicle.
2. Definition of the magnitude of the ozone replenishment problem and the sizing of vehicle or vehicle fleet to meet the requirement.
3. Definition of candidate vehicle geometry and vehicle systems which will meet the requirement.
4. Definition of a satellite system(s) which provides the following information to the flying vehicle(s):

   a. Location of the ozone hole.

b. Any significant weather conditions at flight altitudes.

c. Estimates of the magnitude of the ozone hole.

d. Relative navigation and guidance in the case of a system involving more than one vehicle.

Assumption: Each flight vehicle carries a global positioning satellite (GPS) receiver and is capable of transmitting its position back to a satellite.

5. A model or models of the selected candidate vehicle(s) and satellite system.
6. Posters and diagrams explaining system operations.
7. Narrative explaining system operations, including vehicle launch, recovery, and maintenance.

The size and location of a fixed ground-based system design, or a mobile ground-based system design shall include the following:

1. Definition and sizing of the power source for the system.
2. Definition of the magnitude of the ozone replenishment problem and the sizing of a system to the requirement.
3. Definition of candidate system geometry and components which will meet the requirement.
4. Definition of a satellite system(s) which provides the following information to the ground-based system:

a. Location of the ozone hole.

b. Any significant weather conditions which will affect ozone distribution to high altitudes.

c. Estimates of the magnitude of the ozone hole.

5. A model or models of the selected candidate system and satellite system.
6. Posters and diagrams explaining system operations.
7. Narrative explaining system operation and especially, the mechanism by which the ozone produced at the surface gets to high altitude.

2.3 EXPERIMENTS TO BE RECOMMENDED

Due to the lack of current information on ozone replenishment and/or re-generation in such a cold environment as the Antarctic atmosphere, the Project may propose certain experiments to further facilitate future study and work on the problem of ozone depletion over Antarctica. These experiments shall be defined in terms of the experimental data desired, and the possible steps to be employed in obtaining this data. Precise step-by-step experiments shall not be given. The results of these experiments may then be used to determine the actual method of replenishing the ozone if none has previously been defined.

3 MANAGEMENT PROPOSAL

This section of the proposal outlines how Project Equilibrium is organized. Personnel and responsibilities are given in subsection 3.1. An approximate time-line for the completion of the project is given in subsection 3.2.

3.1 PERSONNEL AND RESPONSIBILITIES

Project Equilibrium is operated by three people. Each person is in charge of specific tasks as implied by their titles: Project Manager, Science Manager, and Systems Manager.

The Project Manager, who is the single point of contact, is in charge of all the administrative aspects of the organization such as personnel time schedules, cost management, and general bookkeeping. The Project Manager also oversees the whole project and coordinates the group's activities. In addition, she is responsible for the following technical areas: power source, electrical generation of ozone, and ozone monitoring techniques.

The Science Manager is responsible for all the science aspects of the project, especially the understanding of the problem, such as meteorology, ozone chemistry, and solution methods.

The Systems Manager oversees all the candidate solutions, specifically vehicle configuration and supporting systems.

Because the group is small, the tasks are generally shared. The size of the group limits the scope of the work performed, but it provides for a dynamic and flexible organizational structure. The organization and division of tasks are summarized in Figure 3.1.

Project Equilibrium

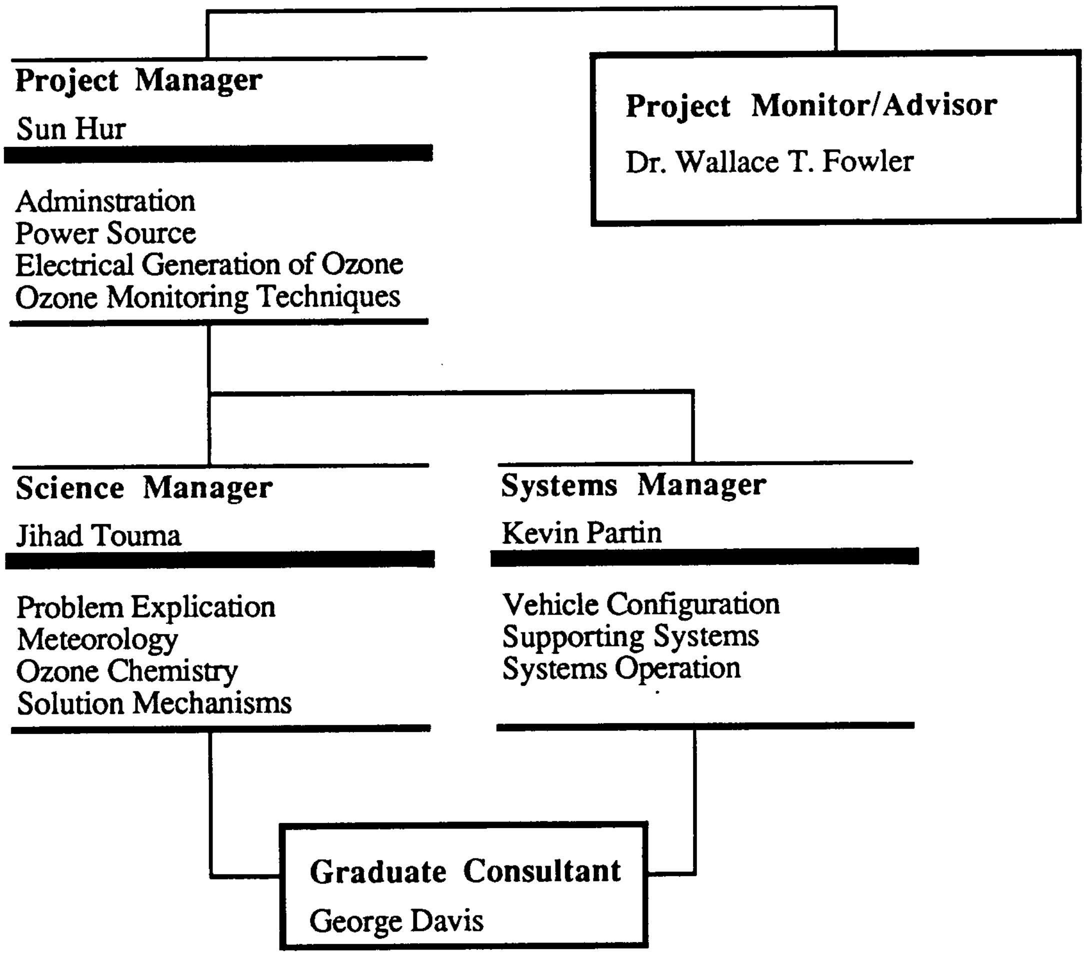

Figure 3.1 Organizational Chart

3.2 PROJECT SCHEDULE

The critical path chart, shown in Figure 3.2, illustrates how the project will progress toward a successful completion of the contract.

The program schedule, shown in Figure 3.3, presents an approximate time-line of the successive phases and milestones of the project. Major milestones are boldfaced. The arrow representing the research phase indicates that it is a continuous activity.

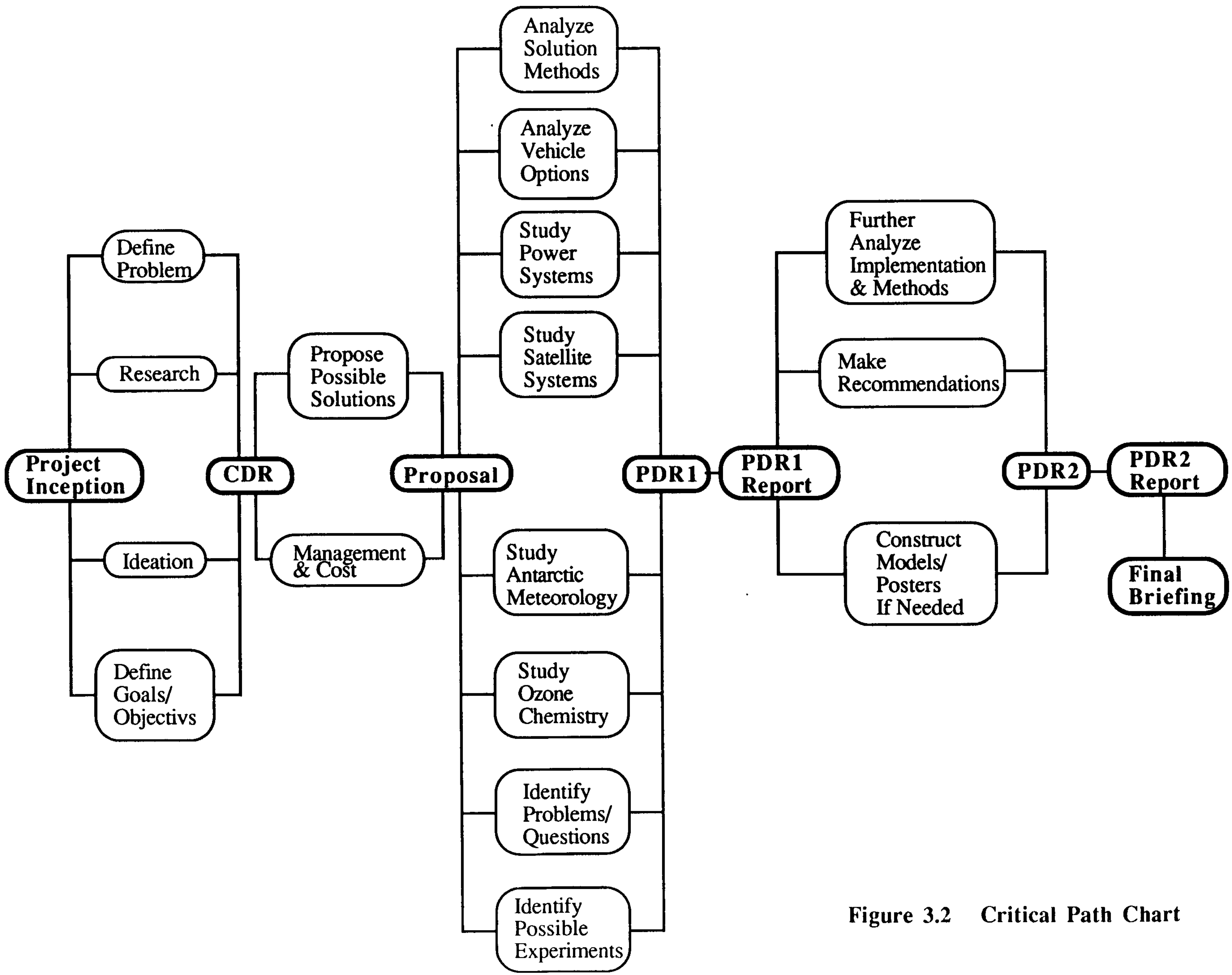

Figure 3.2 Critical Path Chart

PROJECT EQUILIBRIUM
PROGRAM SCHEDULE
Spring 1988

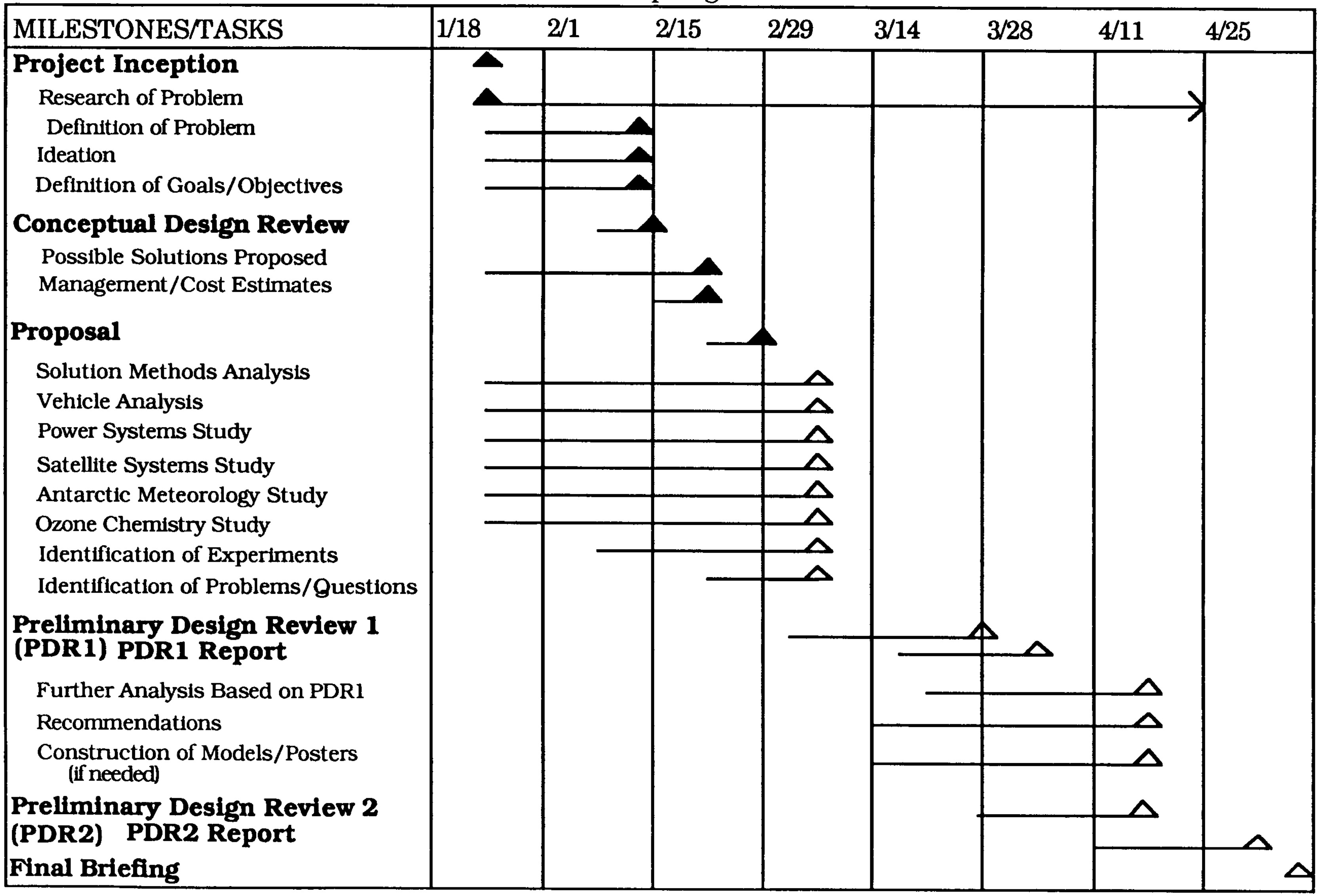

Figure 3.3 Program Schedule

4 COST PROPOSAL

This section outlines the estimates of personnel cost and material and hardware costs associated with performing the contract.

4.1 PERSONNEL COST ESTIMATES

The salaries for each personnel are based on the numbers given in the Request for Proposal. Table 4.1 summarizes the personnel costs.

Table 4.1 Personnel Cost Estimates

Personnel	Hourly Wage	Weekly Hours	Weekly Salary	Sixteen Week Salary
Project Manager	$ 25.00	15	$ 375.00	$ 6,000.00
Science Manager	22.00	10	220.00	3,520.00
Systems Manager	22.00	10	220.00	3,520.00
Consulting	75.00	1	75.00	1,200.00
Subtotal for 16 weeks				$ 14,240.00
Plus 10% error estimate				1,424.00
Total Estimate				$15,664.00

4.2 MATERIAL AND HARDWARE COST ESTIMATES

Costs for material and hardware are based on the cost estimates of previous design groups. Government furnished equipment consists of rental of computer hardware and software.

Table 4.2 Material/Hardware Cost Estimates

Material/Hardware	Sixteen Week Total
2 Macintosh computers/ software/peripherals	$ 1,500.00
IBM PC-AT computer/ software/peripherals	750.00
Photocopies ($0.10 each)	300.00
Transparencies ($0.50 each)	75.00
Travel Expenses	100.00
Miscellaneous	200.00
Subtotal	$ 2,925.00
Plus 10% error estimate	292.50
Total Estimate	$ 3,217.50

4.3 TOTAL ESTIMATED PROJECT COST

Personnel Cost Estimate	$ 15,664.00
Material and Hardware Cost Estimate	3,217.50
Total Estimated Project Cost	$ 18,881.50

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6 PERSONNEL ROSTER

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APPENDIX C

BIOGRAPHY OF GROUP MEMBERS

Sun Hae Hur was born in Seoul, South Korea on September 9, 1966. She and her family immigrated to the United States in 1974. After 4 years in Guam, a U.S. territorial island, they moved to Austin, Texas. Sun entered the University of Texas at Austin (Austin, Texas) in the fall of 1984 and will graduate with a Bachelor of Science degree in Aerospace Engineering in May 1988. She was a member of Sigma Gamma Tau, Tau Beta Pi, Phi Kappa Phi, American Institute of Aeronautics and Astronautics, Students for the Exploration and Development of Space, and Society of Women Engineers. She has also co-oped at Jet Propulsion Laboratory (Pasadena, California) and McDonnell Douglas Astronautics Co. (Houston, Texas). She plans to work at Jet Propulsion Laboratory in the summer of 1988 then continue her education in aeronautics and astronautics at Stanford University (Stanford, California) in the fall.

Permanent Address: 1722 Deerfield Drive
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Kevin Scott Partin will graduate with a Bachelor of Science degree in Aerospace Engineering in May 1988.

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Jihad Rachid Touma was born in Kab-Elias, Lebanon. He entered the department of aerospace engineering at the University of Texas at Austin in the spring of 1985. He will graduate in the summer of 1988 with a B.S in Aerospace Engineering and a B.A in Mathematics. He plans to do graduate work in Applied Mathematics at the Massachusetts Institute of Technology.

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